1

FY90 End of Fiscal Year Letter
(01 Oct 1989 - 30 Sep 1990)

ONR CONTRACT INFORMATION

Contract Title: "Plasma enhanced gas source molecular beam epitaxy deposition of high quality GaN"

Performing Organization: University of Illinois at Urbana-Champaign

Principal Investigator: Hadis Morkoc

Contract Number: N00014-89-J-1780

R & T Project Number: 4145210---06

ONR Scientific Officer: Max Yoder

Enclosure (1)

ONR YEAR END ANNUAL LETTER

A. Scientific Research Goals

GaN is a III-V semiconductor with enormous optical device potential in the near ultraviolet region, a band which has been relatively inaccessible to semiconductor technology. High quality GaN, along with its AlN and InN alloys, would make feasible the production of optically active devices ranging from the visible out to the approximately 6 eV band gap of AlN. Along with its potential benefits come the challenges of this material system. Researchers in the past have been plagued by the inertness of nitrogen which causes GaN films to have a high n-type background carrier concentration resulting from nitrogen vacancies. ~~It is~~ the goal ~~of our~~ investigation to apply electron cyclotron resonance plasma and molecular beam epitaxy technology towards the GaN problem to obtain device quality semiconductor material.

With the growth of high quality cubic GaN this past year, our program has defined itself into two main objectives. Further optimization of the GaN deposition to obtain material of the highest optical and electronic quality will be necessary. Parallel efforts will be undertaken in the related AlN and InN systems. The ability to grow each material will allow these materials to be combined into heterostructure devices analogous to those common in other compound semiconductor systems. We can then investigate the performance of devices designed to operate at shorter wavelengths than are presently available.

A second avenue of activity which can be explored in parallel with the device work will be a cataloging of the properties of the entirely new cubic phases of GaN, InN and AlN. Cubic InN and AlN have never to our knowledge been produced in a laboratory. Comparison of the physical properties of these materials with the established properties of the wurtzite phases would yield interesting insights into the role of crystal structure and its influence on the solid state.

B. Significant Results From FY 1990

Our approach has been to grow GaN on the (100) surface of GaAs. This approach was conceived for several reasons. Foremost, we wished to study the relatively unexplored properties of the cubic phase of GaN and for this we require a cubic substrate. The choice of GaAs was

dictated by the relatively high quality of the substrates and our hope to combine GaAs based devices with GaN surface coatings. GaAs substrates also allow us to grow a GaAs buffer layer and obtain a clean, well understood surface on which to grow GaN.

A great number of GaN/GaAs films were grown this past summer. We have reduced our number of variable growth parameters to a few and were able to grow high quality films. The best films were insulating, with the resistivity being too high for simple measurement on our Hall measurement apparatus. This result is encouraging since it suggests that our material is relatively free of the nitrogen vacancies which have plagued other researchers for as long as this material has been studied. Nomarski phase contrast microscopy revealed fairly smooth surface morphologies which were comparable in quality to GaAs/Si and other lattice mismatched systems. Layers were specular but varied in tint.

Figure 1 shows a sequence of photographs taken of high energy electron diffraction (HEED) patterns during one GaN growth. Figure 1 (a) shows the clean epitaxial (2×4) GaAs (100) surface before GaN growth. When GaN/GaAs growth is initiated this pattern becomes quite spotty indicating initial island formation which is not unusual in mismatched systems. However, the epitaxy becomes two dimensional fairly rapidly as seen in Figure 1 (b) which shows the HEED pattern after 100 Å of GaN deposition. Some roughness is apparent, yet at this point the cubic GaN lattice constant can clearly be discerned and the reconstruction is recognizeable as (2×2). The pattern continues to improve until it is quite sharp (Figure 1 (c)) and remains as such. From the symmetry of the HEED patterns and their spacing it is possible to identify the crystal as cubic having a lattice constant of approximately 4.5 Å . These results were confirmed by x-ray diffraction analysis. The sharpness of the reconstruction indicates a surface which is quite smooth. Smooth surfaces will be necessary for the formation of sharp heterojunctions in GaN/AlGaN optical devices.

Preliminary TEM results from Professor David Smith's lab at Arizona State University indicate that in some layers in which In incorporation was attempted, a slightly larger lattice constant is apparent. This is evidence that we have succeeded in growing cubic $In_xGa_{1-x}N$. Extrapolation

of the lattice constant of this new material should give a reasonable estimate of the cubic InN lattice constant.

The optical quality of the films were investigated through the complementary techniques of photoluminescence and cathodoluminescence. The cathodoluminescence measurements discussed below were performed at the University of Pittsburgh in the Laboratory of Professor Choyke. Cathodoluminescence taken at 77K revealed material of high optical quality (Figure 2). Exciton structure is apparent around the band gap of cubic GaN at roughly 3.26 eV. We have seen no report in the literature describing the observation of significant excitonic peaks in the optical spectra of GaN and we are very encouraged by this data. A broad midgap defect peak of high intensity is also apparent in the cathodoluminescence spectrum.

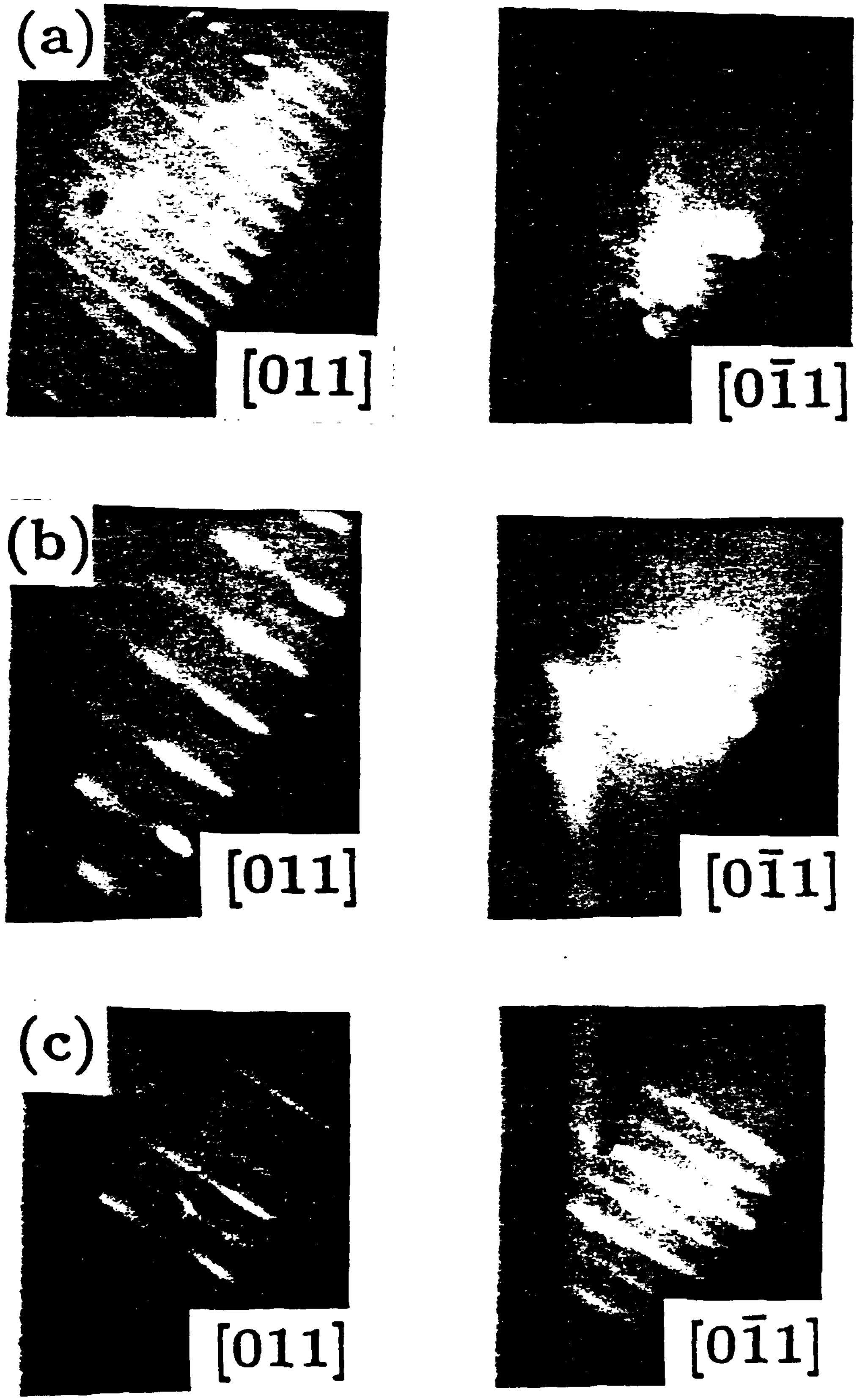
In order to investigate the electrical quality of GaAs/GaN/GaAs heterojunctions, SIS tunneling structures were grown using GaN as the barrier material. Figure 3 gives the layer structure of the devices as well as the temperature dependent current-voltage characteristics. A strong temperature dependence is observed which implies that the majority of current flow is thermionic emission of electrons over a barrier of approximately 0.40 eV. The actual conduction band discontinuity in the GaN/GaAs system is probably significantly larger since the difference in their absolute bandgaps is approximately 1.85 eV (GaN=3.25 eV, GaAs=1.4 eV). These measurements show that GaN provides a fairly large insulating barrier of reasonable quality to electron conduction in GaAs and forms a good interface despite the large inherent lattice mismatch. Such a result is an encouraging one for future investigations of the properties of GaN as a dielectric material for GaAs based devices.

C. Research Goals For FY 1991

Fiscal year 1990 was spent doing the groundwork for growth of the GaN/GaAs heteroepitaxial system. A significant portion of the time was spent troubleshooting our experimental setup, specifically the microwave ion source used to activate the nitrogen. We have identified several problems which caused our experiment to fail and we are in a position to work around these in our future investigations.

In the coming year we plan to continue to improve the quality of our GaN films while attempting some heterostructure devices. Cathodoluminescence measurements suggest that extremely high quality material may be realized once the midgap defect can be greatly reduced or eliminated. This task will be the foremost on our agenda. On the device front, we have obtained some intriguing results in GaAs/GaN/GaAs SIS structures which suggest that GaN-GaAs heterointerfaces are of reasonable quality. We plan to look at the dielectric properties of GaN as a surface coating for GaAs. It will be interesting to study the passivation effects as well as the properties of GaN as an insulating dielectric for possible MOSFET applications.

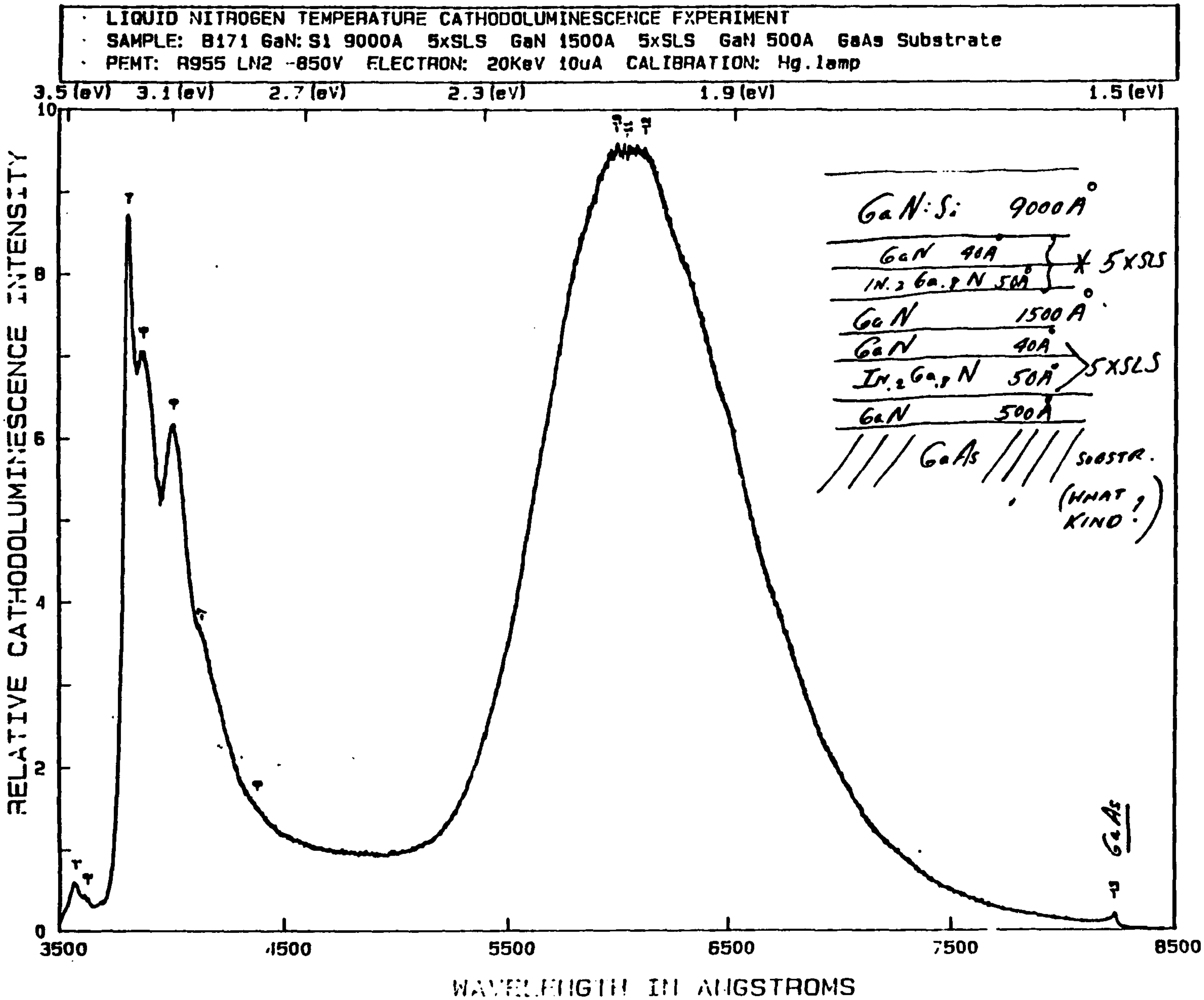
Soon after we optimize our GaN growth techniques we will expand into AlN and InN as well as their alloys with GaN. These heterostructures will be the basis of any optical devices which we wish to attempt in the future. In the past, each of these materials has only been studied in its wurtzite form. Cubic AlN and InN may have novel properties and will be interesting topics of study in their own right. Along these lines we have already gained tantalizing clues as to the nature of cubic InN from our layers which successfully incorporated small amounts on InN into the GaN.


(a)
[011]
[0$\bar{1}$1]
(b)
[011]
[0$\bar{1}$1]
(c)
[011]
[0$\bar{1}$1]

Cubic (100) GaN

JUN 5 - 1990

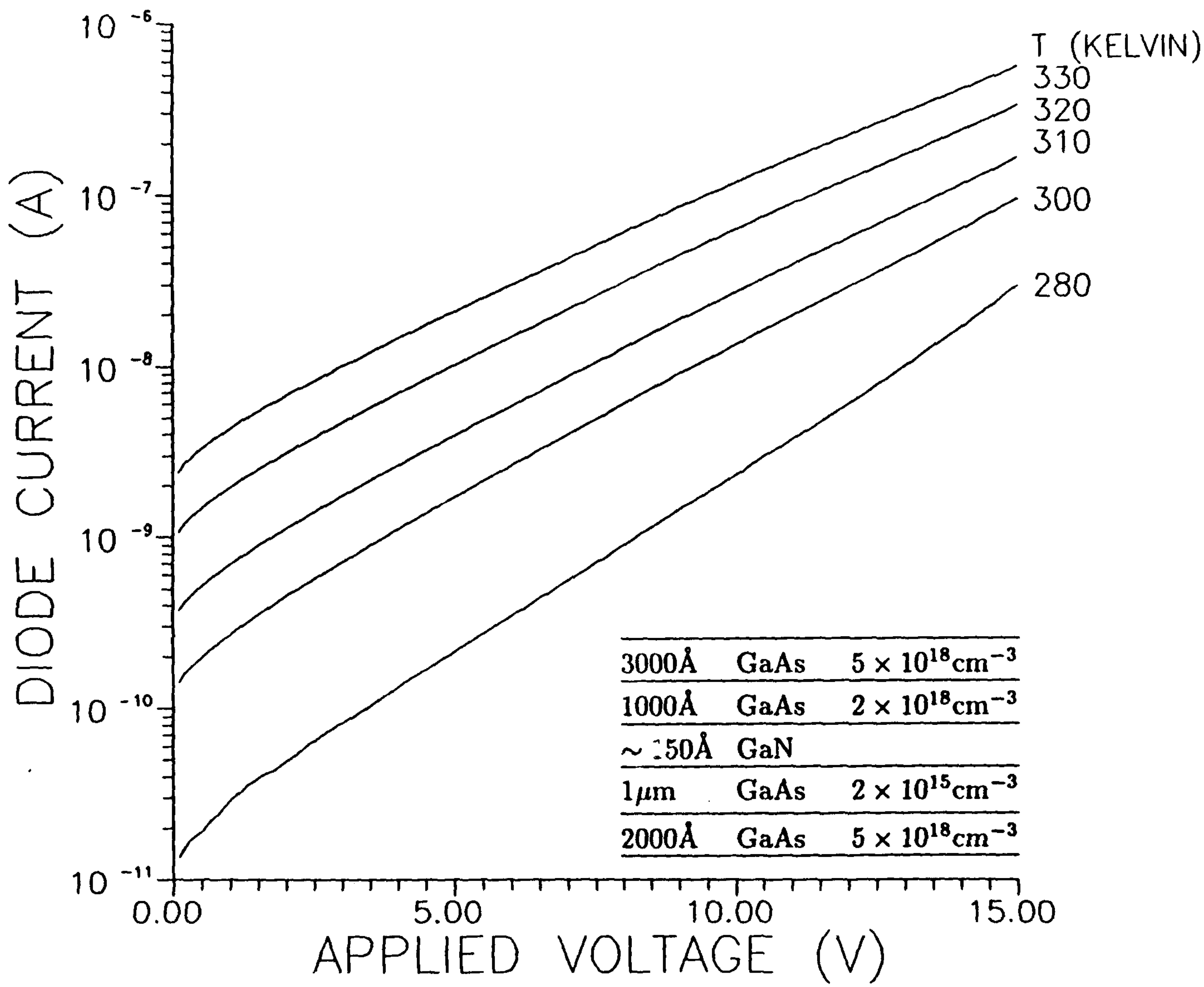
W. J. CHOYKE



MONOCHROMATOR : EBERT
PEM Tube : R955 LN2 -850V
GRATING : 1200 (l/mm) at 7500 (A)

DATE : 6-4-1990	CALIBRATION SOURCE:
FILE : B17102.exp	Hg.lamp
TEMP : 80 (K)	EXCITATION SOURCE:
SLIT 1: 500 (um)	20KeV 10uA
SLIT 2: 500 (um)	SENSITIVITY: 1
STEP-SIZE: 1 (A)	MULTIPLY: 10
	LOCKIN TIME: 1 (s)

NO	WAVELENGTH (A)	ENERGY (eV)	REL. INT.
1	3566	3.476	5.06
2	3616	3.429	4.00
3	3663	3.384	10.30
4	3782	3.280	[illegible]
5	3868	3.204	70.58
6	4004	3.095	61.02
7	4126	3.004	[illegible]
8	4376	2.833	[illegible]
9	5461	2.270	[illegible]
10	5983	2.072	[illegible]
11	6033	2.055	94.02
12	6117	2.026	[illegible]
13	8225	1.507	2.05


DIODE CURRENT (A)
10 -6
10 -7
10 -8
10 -9
10 -10
10 -11
0.00
5.00
10.00
15.00
APPLIED VOLTAGE (V)
T (KELVIN)
330
320
310
300
280
3000Å GaAs 5 × 10^18 cm^-3
1000Å GaAs 2 × 10^18 cm^-3
~ 150Å GaN
1μm GaAs 2 × 10^15 cm^-3
2000Å GaAs 5 × 10^18 cm^-3

D. List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals

None.

2. Non-Refereed Publications and Published Technical Reports

None.

3. Presentations

a. Invited None.

b. Contributed None.

4. Books (and sections thereof)

None.

Enclosure (2)

E. LIST OF HONORS/AWARDS

Name of Person Receiving Award	Recipient's Institution	Name, Sponsor and Purpose of Award
Samuel C. Strite III	University of Illinois at Urbana-Champaign	United States Air Force Laboratory Graduate Fellowship

Enclosure (3)

H. SUMMARY OF FY90
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS/PARTICIPANTS
(Number Only)

		ONR This Project	ONR Other ONR	non ONR
a.	Number of Papers Submitted to Referred Journal but not yet published:	0	5	
b.	Number of Papers Published in Refereed Journals:	0	13	
c.	Number of Books or Chapters Submitted but not yet Published:	0	4	
d.	Number of Books or Chapters Published:	0	0	
e.	Number of Printed Technical Reports & Non-Referred Papers:	0	2	
f.	Number of Patents Filed:	0	0	
g.	Number of Patents Granted:	0	0	
h.	Number of Invited Presentations at Workshops or Prof. Society Meetings:	0	3	
i.	Number of Contributed Presentations at Workshops or Prof. Society Meetings:	0	4	
j.	Honors/Awards/Prizes for Contract/Grant Employees: (selected list attached)	0	4	
k.	Number of Graduate Students and Post-Docs Supported at least 25% this year on contract grant:	3	10	
	Grad Students: TOTAL	3	10	
	Female	1	0	
	Minority	0	0	
	Post Doc: TOTAL	0	1	
	Female	0	0	
	Minority	0	0	
l.	Number of Female or Minority PIs or CO-PIs			
	New Female	0	0	
	Continuing Female	0	0	
	New Minority	0	0	
	Continuing Minority	0	0	

Enclosure (4)

337. S.L. Zhang, M.V. Klein, J. Klem and H. Morkoç, "Raman Scattering from Confined LO Phonons and Dispersion Relation in GaAs/AlGaAs Superlattices," *Phys. Lett. A*, **131**, pp. 69-72, (1988).

338. G. Ji, W. Dobbelaere, D. Huang and H. Morkoç, "Optical Transitions Involving Unconfined Energy States in InGaAs/GaAs Multiple Quantum Wells," *Phys. Rev. B*, **39**, pp. 3216-3222, (1989).

339. L.M. Smith, J.S Preston, J.P. Wolfe, D.R. Wake, J. Klem, T. Henderson and H. Morkoç, "Phonon Wind Driven Transport of Photoexcited Carriers in a Semiconductor Quantum Well," *Phys. Rev. B.*, **39**, pp. 862-870, (1989).

340. T.Won, S. Agarwala, C.K. Peng and H. Morkoç, "Self Aligned $In_{0.52}Al_{0.48}As$/ $In_{0.53}Ga_{0.47}As$ Heterojunction Bipolar Transistors with Graded Interfaces on Semi Insulating InP Grown by Molecular Beam Epitaxy," *IEEE Electron. Dev. Lett.*, **EDL-10(3)** , pp. 138-140, (1989).

341. R.D. Groeber, H.D. Drew, J.I. Chyi, S. Kalem and H. Morkoç, "Infrared Photoluminescence of InAs Epilayers Grown on GaAs and Si Substrates," *J. Appl. Phys.*, **65**, pp. 4079-4081, (1989).

342. K.T. Tsen, O.F. Sankey, G. Halama, S.C.Y. Tsen and H. Morkoç, "Transport of Photoexcited Electron Hole Plasma in GaAs Quantum Wells," *Phys. Rev. B, Rapid Commun.*, **39**, pp. 6276, (1989).

343. F. Xiong, T.A. Tombrello, H. Eang, T.R. Chen, H. Morkoç and A. Yariv, "High Efficiency Single Quantum Well RIN-SCH Lasers Fabricated with MeV Oxygen Implantion," *Appl. Phys. Lett.*, **54**, pp. 730-732, (1989).

344. C. Kiely, J.I. Chyi, A. Rockett and H. Morkoç, "On the Microstructure and Interfacial Structure of InSb Layers Grown on GaAs (100) by Molecular Beam Epitaxy," *Philosophical Magazine*, **60(3)** , pp. 321-337, (1989).

345. M.W. Peterson, J.A. Turner, C.A. Parsons, A.J. Nozik, D.J. Arent, C. Van Hoof, G. Borghs, R. Houdré and H. Morkoç, "Miniband Dispersion in $GaAs/Al_xGa_{1-x}As$ Superlattices with Wide Wells and Very Thin Barrier Layers," *Appl. Phys. Lett.*, **53(26)** , pp. 2666-2668, (1989).

346. D. Huang, D. Mui and H. Morkoç, "Interference Effects Probed by Photoreflectance Spectroscopy," *J. Appl. Phys.*, **66**, pp. 358-361, (1989).

347. M.E. Hoenk, H.Z. Chen, A. Yariv, H. Morkoç and K.J. Vahala, "Cathofoluminescence Measurement of an Orientation Dependent Aluminum Concentration in $Al_xGa_{1-x}As$ Epilayers Grown by Molecular Beam Epitaxy on a Nonplanar Substrate," *Appl. Phys. Lett.*, **54(14)** , pp. 1347-1349, (1989).

348. V.V. Gridin, R. Beserman and H. Morkoç, "Correspondence Between the Dependence of Frequencies and Intensities of GaAs and AlAs Longitudinal Optical Modes on the Photon Energy in a Thin Layer GaAs/AlAs Superlattice," *Phys. Rev. B*, **39**, pp. 1703, (1989).

349. I.Sela, R. Beserman and H. Morkoç, "Resonance Raman Scattering Induced Interface Roughness in a Short Period GaAs/AlGaAs Superlattice," *Phys. Rev. B*, **39**, pp. 3254, (1989).

350. S. Agarwala, T. Won and H. Morkoç, "AlGaAs/GaAs Single Heterojunction Bipolar Transistors Grown on InP by Molecular Beam Epitaxy," *Appl. Phys. Lett.*, **54(12)** , pp. 1151-1153, (1989).

351. M.B. Patil, S.N. Mohammad and H. Morkoç, "Modeling of Field Effect Transistors with Laterally Graded Doping," *Solid State Electronics,* **32(9)** , pp. 791- 795, (1989).

352. S.N. Mohammad, M.B. Patil and H. Morkoç, "Heavy Doping for Improved Short Channel Operation of GaAs MESFETs," *Electronic Lett.,* **25**, pp. 331-332, (1989).

353. J.I. Chyi, D. Biswas, S.V. Iyer, N.S. Kumar, H. Morkoç, R. Bean, K. Zanio, H.Y. Lee and H. Chen, "Molecular Beam Epitaxial Growth and Characterization on InSb on Si," *Appl Phys. Lett.,* **54**, pp. 1016-1018, (1989).

354. H.J. Ou, S.C.Y. Tsen, K.T. Tsen, J.M. Cowley, J.I. Chyi, A. Salvador and H. Morkoç, "Determination of the Local Al Concentration in $Al_xGa_{1-x}As$/GaAs Quantum Well Structures Using (200) Diffraction Intensity Obtained with a 10Å Electron Beam," *Appl. Phys. Lett.,* **54**, pp. 1454, (1989).

355. T.Won, S. Iyer, S. Agarwala and H. Morkoç, "Collector Offset Voltage of Heterojunction Bipolar Transistors Grown by Molecular Beam Epitaxy," *IEEE Electron. Dev. Lett.,* **EDL-10(6)** , pp. 274-276, (1989).

356. G.B. Gao, M.Z. Wang, X. Gui and H. Morkoç, "Thermal Design Studies of High Power Heterojunction Bipolar Transistors," *IEEE Trans. Electron. Dev.,* **ED-36(5)** , pp. 854-863, (1989).

357. P.W. Yu, C.K. Peng and H. Morkoç, "Photoluminescence from Carriers Confined at a $Ga_xIn_{1-x}As$/InP Single Heterojunction Interface," *Appl. Phys. Lett.,* **54(16)** , pp. 1546-1548, (1989).

358. J.I. Chyi, J. Chen, N.S. Kumar, C. Kiely, C.K. Peng, A. Rockett and H. Morkoç, "Low Resistance Nonalloyed Ohmic Contacts on p-Type GaAs Using GaSb/GaAs Strained Layer Superlattices," *Appl. Phys. Lett.,* **55(6)** , pp. 570-571, (1989).

359. J. Chen, G.B. Gao, D. Huang, J.I. Chyi, M.S. Ünlü and H. Morkoç, "Photo Emission from Avalanche Breakdown in the Collector Junction of GaAs/AlGaAs Heterojunction Bipolar Transistors," *Appl. Phys. Lett.,* **55**, pp. 374-376, (1989).

360. D.S.L. Mui, M.B. Patil and H. Morkoç, "Calculation of the Electron Wave Function in a Graded Channel Double Heterojunction Modulation Doped Field Effect Transistor," *Appl. Phys. Lett.,* **55(12)** , pp. 1223-1225, (1989).

361. S.N. Kumar, J.I. Chyi, C.K. Peng and H. Morkoç, "A GaAs Metal Semiconductor Field Effect Transistor with Extremely Low Resistance Non-Alloyed Ohmic Contacts Using an InAs/GaAs Superlattice," *Appl. Phys. Lett.,* **55**, pp. 775-776, (1989).

362. J. Chen, G.B. Gao, J.I. Chyi and H. Morkoç, "Breakdown Behavior of GaAs/AlGaAs HBTs," *IEEE Trans. Electron. Dev.,* **ED-36(10)** , pp. 2165-2172, (1989).

363. M.S. Ünlü, S. Strite, S.N. Mohammad, K. Adomi, T. Won and H. Morkoç, "Characteristics of p-Ge/n-GaAs Heterojunctions Grown by Molecular Beam Epitaxy," *Electronic Lett.,* **24(20)** , pp. 1359-1360, (1989).

364. M.S. Ünlü, G.B. Gao, T. Won, S.V. Iyer, J. Chen and H. Morkoç, "500 mA AlGaAs/GaAs Power Heterojunction Bipolar Transistor," *Electronic Lett.* **25(21)** , pp. 1447-1449, (1989).

365. U.K. Reddy, G. Ji, T. Henderson, D. Huang, R. Houdré, H. Morkoç and C.W. Litton, "Interband Transistions in InGaAs/GaAs Strained Layer Superlattices," *J. of Vac. Sci and Technol.,* **B7(5)** , pp. 1106-1110, (1989).

366. B. Kh. Bairamov, T. Gant, M. Delaney, Y.E. Kitaev, M.V. Klein, D. Levi, H. Morkoç and R.A. Everestov, "A Theoretical and Experimental Investigation of Raman Scattering in the Size-quantizing Heterostructure Superlattices $(GaAs)_m$ $(AlAs)_n$," *Sov. Phys. JETP,* **68(6)** , pp. 1271- 1276, (1989).

367. D. Mui, M. Patil, J. Chen, N.S. Kumar and H. Morkoç, "Modeling of the I-V Characteristics of Single and Double Tunneling Diodes Using a $k \cdot p$ Band Model," *Solid State Electronics,* **32(11)**, pp. 1025-1031, (1989).

368. S.N. Mohammad, M.B. Patil, J.J. Chen, M.S. Ünlü, G.B. Gao and H. Morkoç, "Analytical Model for I-V Characteristics of Ion Implanted MESFETs," *IEEE Trans. Electron. Dev.,* **ED-37**, pp. 11-20, (1990).

369. S.N. Mohammad, M.B. Patil, J.J. Chen, M.S. Ünlü, and H. Morkoç, "Analytical Model for I-V Characteristics of JFETs with Heavily Doped Channels" *Solid State Electronics,* **33(1)**, pp. 53-64, (1990).

370. M.B. Patil and H. Morkoç, "Self-Consistent Calculation of Electron Density in a Two-Channel Modulation Doped Structure," *Solid State Electronics,* **33(1)**, pp. 99-104, (1990).

371. K. Adomi, S. Strite and H. Morkoç, "Antiphase Domain Free GaAs Grown on Pseudomorphic Si (100) Vicinal Surfaces by Molecular Beam Epitaxy," *Appl. Phys. Letts.,* **56(5)**, pp. 469-471, (1990).

372. S. Strite, D. Biswas, K. Adomi and H. Morkoç, "Study of Sublattice Orientation of GaAs on Ge," *J. Appl. Phys. Lett.,* **67(3)**, pp. 1609-1612, (1990).

373. M.S. Ünlü, S. Strite, K. Adomi, G.B. Gao and H. Morkoç, "Extremely Low-Resistance Non-alloyed Ohmic Contacts on Molecular Beam Epitaxially Grown p-type Ge," *Electronic Letts.,* **26(2)**, pp. 89-91, (1990).

374. H.J. Ou, J.M. Cowley, J.I. Chyi, A. Salvodor and H. Morkoç, "Microanalysis on the (200) Diffraction Intensity to Determine the Al Concentration for AlGaAs/GaAs MQWS Structures," *J. Appl. Phys.,* **67(2)**, pp. 698- 704, (1990).

375. G. Ji, D. Huang, T. Henderson, C.K. Peng and H. Morkoç, "Analysis of Energy States in Modualtion Doped Multiquantum Well Heterostructures," *Solid State Electronics,* **2**, pp. 247-258, (1990).

376. G.B. Gao, D. Huang, J. Chyi, J. Chen and H. Morkoç, "Current Induced Breakdown in P-Type Collector AlGaAs/GaAs HBTs," *IEEE Trans. on Electron. Dev.,* **37(3)**, pp.807-810, (1990).

377. M.S. Ünlü, S. Strite, K. Adomi, G.B. Gao and H. Morkoç, "Extremely Low Resistance Nonalloyed Ohmic Contacts on Molecular Beam Epitaxially Grown P-Type Ge," *Electronic Letts.,* **26(2)**, pp, 89-90, (1990).

378. S. Strite, M.S. Ünlü, K. Adomi and H. Morkoç, "Si as a Diffusion Barrier for Ge/GaAs Heterojunctions", *Appl. Phys. Lett.,* **56(17)**, pp. 1673-1675, (1990).

379. S. Strite, D. Biswas, N.S. Kumar, M. Fradkin and H. Morkoç, "Antiphase Domain Free Growth of GaAs on Ge in GaAs/Ge/GaAs Heterostructures," Submitted to *Appl. Phys. Lett.,* **56(3)**, pp. 244-246, (1990).

380. S.N. Mohammad, J. Chen, J. Chyi and H. Morkoç, "Suppression of Emitter Size Effect on the I-V Characteristics of GaAs/AlGaAs Heterojunction Bipolar Transistors," *Appl. Phys. Lett.*, **56(10)**, pp. 937-939, (1990).

381. G.B. Gao, D.J. Roulston and H. Morkoç, "Design Study of AlGaAs/GaAs HBTs," *IEEE Trans. on Electron. Dev.*, **37(5)**, pp. 1199-1208, (1990).

382. M.S. Ünlü, S. Strite, G.B. Gao, K. Adomi and H. Morkoç, "Electrical Characteristics of p^+-Ge/(N-GaAs and N-AlGaAs) Junctions and Their Applications to Ge Base Transistors," *Appl. Phys. Lett.*, **56(9)**, pp. 842- 844, (1990).

383. I. Adesida, A. Ketterson, J. Laskar, S. Agarwala, T. Brock, J. Kolodzey and H. Morkoç, "0.2μm T-Gate InAlAs/InGaAs MODFET with F_T = 170 GHz," *Microelectronic Engineering*, **11**, pp. 69-72, (1990).

384. P. Roblin, S.C. Kang and H. Morkoç, "Analytic Solution of the Velocity-Saturated MOSFET/MODFET Wave Equation and Its Application to the Prediction of the Microwave Characteristics of MODFET's," *IEEE Trans. on Electron. Dev.*, **37(7)**, pp. 1608-1622, (1990).

385. K. Shum, Y. Takiguchi, J.M. Mohaidat, F. Liu, R.R. Alfano and H. Morkoç, "Picosecond Hole Dynamics of in GaAs Grown on Silicon," *Appl. Phys. Lett.*, **56(23)**, pp. 2328-2330, (1990).

386. A. Salvador, J. Reed, N.S. Kumar, M.S. Unlu and H. Morkoç, "Electroabsorption Studies on GaAs Asymmetric Coupled Quantum Wells," *Surface Science*, **228**, 188-191, (1990).

387. D.S.L. Mui, A. Salvador, S. Strite and H. Morkoç, "Effect of Thin Ge Layer on the Surface Depletion in GaAs," *Appl. Phys. Lett.*, **57(6)**, pp. 572-574, (1990).

388. D. Huang, J.I. Chyi and H. Morkoç, "Carrier Effects on the Excitonic Absorption in GaAs Quantum Well Structures: Phase-Space Filling," *Phys. Rev. B*, **42(8)**, 5147-5153, (1990).

389. M.S. Ünlü, K. Kishino, J.I. Chyi, L. Arsenault, J. Reed, S.N. Mohammad and H. Morkoç, "Resonant Cavity Enhanced AlGaAs/GaAs Heterojunction Phototransistors with an Intermediate InGaAs Layer in the Collector," *Appl. Phys. Letts.*, **57(8)**, 750-752, (1990).

390. H.J. Ou, J.C. Barry, J.M. Cowley and H. Morkoç, "Distributions of the Al Concentration in $Al_xGa_{1-x}As$ Layer of $Al_xGa_{1-x}As$ MQWS Structure," Submitted to *Appl. Phys. Lett*, pending.

391. L.E. Eng, T.R. Chen, S.Sanders, Y.H. Zhuang, B. Zhao, A. Yariv and H. Morkoç, "Sub Milliampere Threshold Current Pseudomorphic InGaAs/AlGaAs Buried Heterostructure Quantum Well Lasers Grown by Molecular Beam Epitaxy," Submitted to *Appl. Phys. Lett.*.

392. T.N. Krabach, A.L. Kotz, M.V. Klein, N.S. Kumar and H. Morkoç, "Brillouin Scattering Measurements of Elastic Constants of $Al_xGa_{1-x}As$," Submitted to *Phys. Rev. Lett.*.

393. G.B. Gao, D.J. Roulston and H. Morkoç, "Is Npn or Pnp the Better Choice for Millimeter Wave AlGaAs/GaAs HBTs?," Submitted to *Solid State Electronics*, in press.

394. K. Shum, K.S. Wong, H.S. Chao, R.R. Alfano, S.V. Iyer and H. Morkoç, "Picosecond Dynamics of Exciton Capture by Neutral Carbon Acceptors in GaAs Quantum Wells," Submitted to *Phys. Rev. B*, pending.

395. G.B. Gao, J.I. Chyi, J. Chen and H. Morkoç, "Emitter Region Delay Time of AlGaAs/GaAs Heterojunction Bipolar Transistors," Submitted to *Solid State Electronics*, in press.

396. S. Strite, M.S. Ünlü, K. Adomi, G.B. Gao and H. Morkoç, "AlGaAs/Ge/GaAs Heterojunction Bipolar Transistors Grown by Molecular Beam Epitaxy," Submitted to *IEEE Electron. Dev. Lett.*, pending.

397. K.Shum, H.S. Chao, R.R. Alfano, S.V. Iyer and H. Morkoç, "Hydrogen-Molecule-Like Complex in Undoped GaAs Quantum Wells," Submitted to *Phys. Rev. Letts.*, pending.

398. K.T. Tsen, G. Halama, O.F. Sankey, S.C.Y. Tsen and H. Morkoç, "Time Resolved Raman Studies of the Photoexcited Electron Hole Plasma in InP," Submitted to *Phys. Rev. B Rapid Commun.*, in press.

399. E.D. Specht, G.E. Ice, C.J. Peters, C.J. Sparks, N. Lucas, H. Morkoç and X.M. Zhu, "X-Ray Diffraction Measurement of Interface Structure in GaAs/Si (001)," Submitted to *Phys. Rev. B*, pending.

400. S. Strite, M.S. Ünlü, K. Adomi, G.B. Gao, A. Agarwal, A. Rockett, H. Morkoç, D. Li, Y. Nakamura and N. Otsuka"GaAs/Ge/GaAs Heterostructures by Molecular Beam Epitaxy", Submitted to *J. Vac. Sci. and Tech.*, pending.

401. S.N. Mohammad and H. Morkoç, "Optically Controlled Current-Voltage Characteristics of Ion-Implanted MESFETs," Submitted to *Solid State Electron.*, in press.

402. G.B. Gao, M.S. Ünlü, and H. Morkoç, "Emitter Ballasting Resistor Design for, and Current Handling Capability of AlGaAs/GaAs Power Heterojunction Bipolar Transistors," Submitted to *IEEE Trans. on Electron Dev.*,, pending.

403. H. Morkoç, "MODFETs Reach New Heights with Cut- Off Frequencies over 400 GHz," Submitted to *IEEE Circ. and Dev. Magazine*, pending.

404. H. Morkoç and G.B. Gao, "Heterojunction Bipolar Transistors (HBTs) Crack the 200 GHz Barrier," Submitted to *IEEE Circ. and Dev.*, pending.

405. A. Salvador, J. Reed, M.S. Ünlü, T.C. Shen, L. Arsenault and H. Morkoç, "Electroabsorption in Strongly Coupled Asymmetric Quantum Wells," Submitted to *Appl. Phys. Letts.*, pending.

406. A. Salvador, K. Adomi, K. Kishino, M.S. Ünlü and H. Morkoç, "GaAs Multiple Quantum Well Reflector Modulators Grown on Si," Submitted to *Appl. Phys. Letts.*, pending.

407. J.I. Chyi, D. Mui, J. Chen and H. Morkoç, "Electrical Characteristics of InSb/GaAs Heterojunctions," Submitted to *Applied Phys. Letts.*, pending.

408. M.S. Ünlü, G.B. Gao, K. Adomi, J. Chen, G.X. Liu and H. Morkoç, "Double Layer Collector Power AlGaAs/GaAs Heterojunction Bipolar Transistors on Si," Submitted to *IEEE Electron Dev. Letts.*, pending.

409. M.S. Ünlü, K. Kishino, J.I. Chyi, L. Arsenault, J. Reed and H. Morkoç, "Wavelength Demultiplexing Heterojunction Phototransistor," Submitted to *Electronic Letts.*, pending.

410. K. Adomi, S. Strite, H. Morkoç, Y. Nakamura and N. Otsuka, "Characterization of the GaAs on Si Interface Using a Si Interlayer Grown on GaAs Substrates," Submitted to *J. Appl. Phys.*, pending.

411. S.N. Mohammad, J. Chen, J.I. Chyi and H. Morkoç, "The Effect of Base Doping Gradients on the Electrical Performance of AlGaAs/GaAs Heterojunction Bipolar Transistors," *Appl. Phys. Letts.*, in press.

412. R.K. Ahrenkiel, B.M. Keyes, T.C. Shen, J.I. Chyi and H. Morkoç, "Minority-Carrier Lifetime in $Al_xGa_{1-x}as$ Grown by Molecular Beam Epitaxy," Submitted to *J. Appl. Phys.*, pending.

413. B. Mazhari, G.B. Gao and H. Morkoç, "Collector- Emitter Offset Voltage in Heterojunction Bipolar Transistors," Submitted to *Solid State Electronics*, pending.

414. J. Chen, G.B. Gao and H. Morkoç, "The Thermal Dependence of HBT High-Frequency Performance," submitted to *IEE Electronic Letters*, pending.

415. J.C. Costa, F. Williamson, T.J. Miller, K. Beyzavi, M.I. Nathan, D.S.L Mui, S. Strite and H. Morkoç, "Barrier Height Variation in Al/GaAs Schottky Diodes with a Thin Silicon Interfacial Layer," Submitted to *Appl. Phys. Lett.*, pending.

416. D.S.L. Mui, K.R. Evans, S.F. Fang and H. Morkoç, "Use of Methane in an Electron Cyclotron Resonance Source for Carbon Doping in GaAs Molecular Beam Epitaxy," Subimitted to *Appl. Phys. Lett.*, pending.

417.